

Available online at www.sciencedirect.com**ScienceDirect**

Energy Procedia 114 (2017) 4056 – 4061

Energy

Procedia

13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18
November 2016, Lausanne, Switzerland

Monitoring results after 36 ktonnes of deep CO₂ injection at the Aquistore CO₂ Storage Site, Saskatchewan, Canada

Don White^{a,*}, Kyle Harris^{a,b}, Lisa Roach^c, Brian Roberts^a, Kyle Worth^d, Anna Stork^e,
Christopher Nixon^f, Douglas Schmitt^f, Tom Daley^g, Claire Samson^b

^aGeological Survey of Canada, Ottawa, K1A 0E, Canada

^bCarleton University, Ottawa, Canada;

^cLeeds University, Leeds, UK

^dPetroleum Technology Research Centre, Regina, Canada

^eBristol University, Bristol, UK

^fUniversity of Alberta, Edmonton, Canada

^gLawrence Berkeley National Laboratory, Berkeley, USA

Abstract

The Aquistore CO₂ Storage Site is located in southeastern Saskatchewan, Canada. CO₂ is injected into a brine-filled sandstone formation at ~3200 m depth immediately above the Precambrian basement. Sustained injection rates of 400-600 tonnes/day were achieved at the site starting in the fall of 2015 with a total of 88 ktonnes having been injected by the end of September, 2016. Seismic monitoring methods have been employed to track the subsurface CO₂ plume and to record any injection-induced seismicity. Passive seismic monitoring is being conducted using two orthogonal arrays of short-period geophones, 3 broadband seismographs, and an array of downhole geophones. No significant injection-related seismicity (Mw > -1) has been detected during the first 17 months of CO₂ injection. The first post-injection time-lapse 3D seismic surveys (surface and VSP) were conducted at the site in February, 2016. The VSP data were acquired with a distributed acoustic sensing system using a 2750 m casing-conveyed optical fibre cable in the observation well. 3D seismic modelling of fluid flow simulations in conjunction with seismic repeatability estimates obtained from field data indicate that the time-lapse VSP should be capable of imaging the CO₂ plume after a total injection of ~30 ktonnes. In addition, this first monitor survey tests the ability of surface seismic data acquired with a sparse permanent array to detect or image the CO₂ plume after limited injection. Time-lapse logging is being conducted on a regular basis to provide in situ measurement of the change in seismic velocity associated with changes in CO₂ saturation.

Crown Copyright © 2017 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the organizing committee of GHGT-13.

* Corresponding author. Tel.: +1-613-220-7963; fax: +1-613-943-9285.

E-mail address: don.white@canada.ca

Keywords: storage; monitoring; seismic; 4D

1. Introduction

The Aquistore CO₂ Storage Site is located in southeastern Saskatchewan, Canada. CO₂ is captured at SaskPower's Boundary Dam coal-fired power plant and is transported via pipeline to the storage site where it is injected at ~3200 m depth into a brine-filled sandstone reservoir (Winnipeg and Deadwood formations) lying immediately above the Precambrian basement. Following the start-up of CO₂ injection in April, 2015, sustained injection rates of 400-600 tonnes/day were achieved in the fall of 2015. A total of 87 ktonnes of CO₂ was injected by the end of September, 2016.

The Aquistore Project includes a comprehensive measurement, monitoring and verification (MMV) program [1] which includes passive seismic monitoring for induced seismicity, time-lapse 3D seismic imaging to track the CO₂ plume in the subsurface, and time-lapse logging to measure in situ changes in the reservoir seismic properties due to CO₂ replacement of brine. Here, we report on results of these particular monitoring activities conducted during the first 17 months of CO₂ injection.

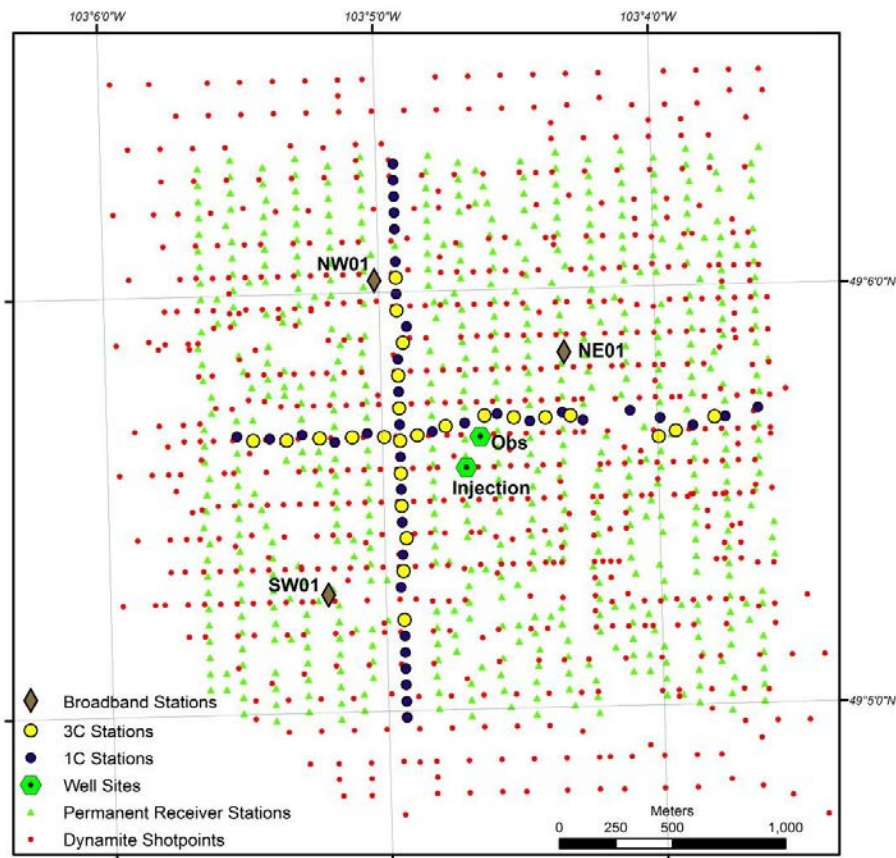


Figure 1. Aquistore site map showing locations of injection well, observation (Obs) well, permanent geophone array, broadband seismographs, and dynamite shot stations for the time-lapse 3D surface seismic and VSP.

2. Passive Seismic Monitoring

Passive seismic monitoring was initiated at the Aquistore site in August, 2012. This has allowed the recording of almost 3 years of local background seismicity prior to the onset of CO₂ injection in April, 2015 followed by 18 months of monitoring after the start of CO₂ injection [2]. Four different monitoring systems (Figure 1) have been utilized for this purpose, each with its own specific objectives.

2.1 Broadband surface seismographs

3 Guralp CMG-40T (0.1-50 Hz) seismometers are deployed at the surface at distances of ~1 km from the injection well (SW01, NW01 and NE01 in Figure 1). Data is transmitted to the Canadian National Seismograph Network data centre where it is available for download and analysis in near real-time. These stations have been recording since installation in November, 2013. The broadband stations are designed to provide near real-time event detection capability for either microseismic activity ($M_w > 0.1$) or potentially larger magnitude induced seismic events. During the initial stages of injection and during any non-routine injection operations, the seismic analysis was done on a daily basis. Otherwise, data analysis and reporting is done on a weekly to monthly basis.

2.2 Short-period surface geophone array

65 10 Hz geophones are deployed at ~72 m intervals along two 2.5 km long, orthogonal linear lines (1C and 3C in Figure 1). The geophones comprise a mix of vertical-component (1C) and 3-component (3C) geophones, and are buried at 20 m (1C) or 6 m (3C) depth, respectively. Data at each geophone station are recorded by an autonomous field recorder with data upload occurring on a monthly basis. This continuously monitoring array is designed to provide a complete record of local seismicity for magnitudes of $M_w > -1$. It has the advantage that multi-channel processing methods can be applied to the data allowing enhancement of the sensitivity of the monitoring system. However, it only provides microseismic reporting weeks after events may have occurred.

2.3 Downhole geophone array

5 3C (15 Hz) downhole geophones were deployed during the first 8 months of injection, from May 2016-December-2016. The tool was deployed in the observation well (Obs in Figure 1) over the depth range of 2850-2910 m (that is ~250 m above the reservoir) and operated continuously at temperatures of 115°C. The tool was retrieved periodically for repair, maintenance and when the well was required for logging purposes. Each time the tool was deployed, 1 kg dynamite charges were detonated at two distant surface locations in order to determine the orientation of the geophones in the well. The downhole monitoring was intended to extend the magnitude threshold for event detection to $M_w > -3$ so that a complete record of microseismic activity could be achieved for comparison with geomechanical modeling and reservoir response to injection.

2.4 Downhole distributed acoustic sensing (DAS)

In April-2015 a short-term test of passive seismic monitoring was conducted using the fibre optic cable that is cemented external to the casing in the observation well (Obs in Figure 1) extending from the surface to a depth of ~2700 m. 35 days of passive data were recorded. The purpose of this experiment was to assess the utility of distributed acoustic sensing (DAS) as a potential alternative to downhole geophone systems for microseismic monitoring. Evaluation of the data acquired during this test is ongoing.

Event detection methods including direct inspection, application of short-term average/long-term average (STA/LTA) detection algorithms and multi-channel stacking methods have variably been applied to the data from each of the monitoring systems itemized in 2.1 to 2.4. No significant injection-related seismicity ($M_w > -1$) has been detected during the first 17 months of CO₂ injection, nor smaller magnitude seismicity ($M_w > -3$) during the first 8 months when the downhole array was active. Further analysis of the downhole and surface passive data is on-going

to detect smaller magnitude microseismicity.

3. Time-lapse 3D seismic monitoring

The depth of the Aquistore reservoir poses a serious challenge for seismic imaging of the CO₂ plume. Both 3D vertical seismic profiling (VSP) and 3D surface seismic are being employed at the site for time-lapse seismic monitoring: the former designed to image the plume within 500 m of the injection well, and the latter suited for ongoing time-lapse monitoring at the site as the plume expands. 3D seismic modelling of fluid flow simulations [3] in conjunction with seismic repeatability estimates obtained from field data [4] indicate that the time-lapse VSP should be capable of imaging the CO₂ plume after a total injection of ~30 ktonnes. Surface 3D time-lapse seismic monitoring would be expected to be less sensitive than the VSP monitoring although the use of a permanent seismic array increases sensitivity by reducing time-lapse noise for the surface 3D data [5].

The first time-lapse 3D seismic surveys were conducted at the site in February, 2016 [6]. Both surface 3D seismic and 3D (VSP) were acquired to compare against pre-injection baseline surveys acquired in 2012 [4] and 2013 [3,7], respectively. The VSP data were acquired with a DAS system using a fibre permanently cemented on the outside of the casing in the observation well. Figure 2 displays the time-lapse amplitude differences for both the surface 3D [6] and preliminary results from the 3D VSP for a horizon within the upper Deadwood formation of the reservoir. In both images, an increase in the amplitude differences is observed toward the edges of the images; this is an expected result of the survey geometry and results from an increase in time-lapse noise toward the periphery of the area. However, near the centre of the images in the vicinity of the CO₂ injection well, a clear amplitude anomaly is observed in both of the images where the amplitude difference is well above the background time-lapse noise level. This amplitude difference anomaly is most simply interpreted as a representation of the CO₂ plume at this depth with the “brightness” (i.e., magnitude of the nRMS difference) being related to the mean CO₂ saturation over the resolved depth interval. This interpretation indicates that the CO₂ plume is not symmetric about the injection well. The highest amplitude lobe, most simply interpreted as the zone of highest CO₂ saturation, appears to extend northward from the injection well for a distance of up to 200 m. The VSP image suggests that the CO₂ plume may reach the observation well (in contrast to the surface image), but with lower saturation based on the strength of the anomaly. The observed asymmetry in the CO₂ plume at this level contrasts with early flow simulations [8] and will require adjustment of the permeability characteristics of the existing geological model.

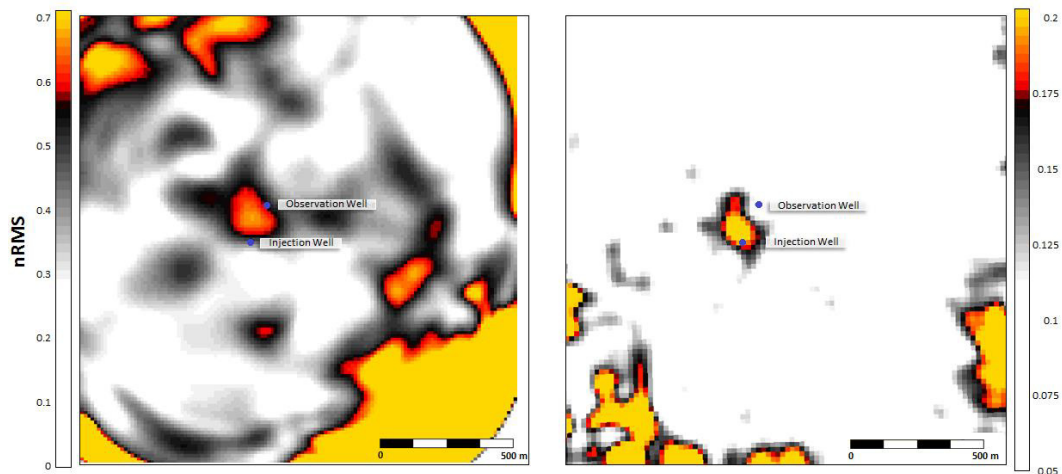


Figure 2. Horizontal depth slice through the 3D time-lapse volumes for (left) VSP (preliminary result), and (right) surface seismic [6], corresponding to a depth interval of ~3165–3185 m. Shown is the normalized RMS amplitude difference determined for the respective 2016 monitor surveys relative to the pre-injection baseline survey. The locations of the injection and observation wells are also shown. Right panel is modified from [6].

4. Time-lapse logging

Cross-dipole sonic logs (CXD) have been acquired in the Aquistore observation well prior to the start of CO₂ injection (baseline) and subsequently at 5 times during the first year of CO₂ injection. Pulsed neutron decay (PND) logs were acquired at the same time with the objective of correlating CO₂ saturation and seismic parameter changes (V_p, V_s, density) in the reservoir. The post-injection sonic logs are largely consistent (i.e., repeatable) but include several zones of reduced V_p within the reservoir zone. These zones do not generally correspond to intervals of CO₂ saturation identified by coincident PND logging making the reliability of the sonic logs uncertain within the reservoir depth range. Further analysis of the sonic log data is underway to better understand the reliability of the logs and the relationship of the observed time-lapse changes to CO₂ saturation and well casing conditions.

Table 1. Joint CXD and PND logging schedule

Date	CO ₂ Injected (tonnes)
Apr-08-2015	0
Apr-20-2015	825
Apr-21-2015	1040
Apr-23-2015	1325
Mar-19-2016	48,100
Apr-02-2016	53,100

5. Conclusions

- No significant injection-related seismicity (M_w > -1) has been detected at the surface during the first 17 months of CO₂ injection. Furthermore, downhole recording over the first 8 months of CO₂ injection also detected no smaller magnitude (M_w > -3) injection-related seismicity. The lack of microseismic activity is surprising particularly because the CO₂ injection interval is directly above and extends into the Precambrian basement.
- Results from the February, 2016 monitor 3D time-lapse seismic surveys (surface and VSP) outline a zone of CO₂ saturation within the upper Deadwood formation of the reservoir. This zone is not symmetric about the injection well, but appears to extend northward from the injection well for a distance of up to 200 m. The VSP image suggests that the CO₂ plume may have reached the observation well by this time, but with relatively low mean saturation over this interval. 36 ktonnes of CO₂ had been injected at the time of the survey.
- Attempts to directly correlate in situ changes in seismic parameters with CO₂ saturation levels using time-lapse CXD and PND logs has been unsuccessful so far. Further work is being done on the CXD raw waveform data toward achieving this objective.

Acknowledgements

Aquistore is an independent research and monitoring project managed by the Petroleum Technology Research Centre (PTRC) which intends to demonstrate that storing liquid carbon dioxide (CO₂) deep underground (in a brine and sandstone water formation), is a safe, workable solution to reduce greenhouse gases (GHGs). Partial funding for this research was provided by: PTRC, Geological Survey of Canada, Natural Sciences and Engineering Research Council of Canada (NSERC) Visiting Fellowship Program; SaskPower; ecoENERGY Innovation Initiative Program of Natural Resources Canada; the EPSRC Geological Storage consortium DiSECCS (EP/K035878/1); EPSRC Early Career Fellowship (EP/K021869/1); the Carbon Storage Program, U.S. DOE, Assistant Secretary for Fossil Energy,

Office of Clean Coal and Carbon Management through the National Energy Technology Laboratory, of the U.S. Department of Energy, under contract No. DE-AC02-05CH11231; Chevron.

References

- [1] Worth, K., White, D., Chalaturmyk, R., Sorensen, J., Hawkes, C., Rostron, B., Risk, D., Young, A., and Sacuta, N., 2016. Aquistore: Year One – Injection, Data, Results, GHGT-13 Proceedings, Energy Procedia, this volume.
- [2] Stork, A.L., Nixon, C., Schmitt, D.R., White, D.J., Kendall, J.-M., and Worth, K., 2016. The seismic response at the Aquistore CO2 injection project, Saskatchewan, Canada, Seismological Research Letters, 87(2B), 477, doi:10.1785/0220160046.
- [3] Harris, K., White, D., Melanson, D., Samson, C., and Daley, T., 2016. Feasibility of Time-lapse VSP Monitoring at the Aquistore CO2 Storage Site Using a Distributed Acoustic Sensing System, International Journal of Greenhouse Gas Control, 50, 248-260. <http://dx.doi.org/10.1016/j.ijggc.2016.04.016>.
- [4] Roach LAN, White DJ, Roberts B. Assessment of 4D seismic repeatability and CO2 detection limits using a sparse permanent land array at the Aquistore CO2 storage site. GEOPHYSICS 2015; 80(2): WA1-WA13 doi:10.1190/geo2014-02011.
- [5] White DJ, Roach LAN, Roberts B. Time-lapse seismic performance of a sparse permanent array: Experience from the Aquistore CO2 storage site: GEOPHYSICS 2015; 80(2): WA35-WA48. doi: 10.1190/geo2014-02391.
- [6] Roach, L.A.N., White, D.J., Roberts, B., and Angus, D., 2016. Initial results from a post-CO2-injection 4D seismic analysis at the Aquistore CO2 storage site, submitted to Geophysics.
- [7] Miller, D.E., Daley, T.M., White, D., Freifeld, B.M., Robertson, M., Cocker, J., and Craven, M., 2016. Simultaneous Acquisition of Distributed Acoustic Sensing VSP with Multi-mode and Singlemode Fibre Optic Cables and 3C-Geophones at the Aquistore CO2 Storage Site, CSEG Recorder, 28-33.
- [8] Jiang, T., Pekot, L.J., Jin, L., Peck, W.D., Gorecki, C.D., Steadman, E.N., Harju, J.A., and Worth, K., 2016. Numerical modelling of the Aquistore CO2 Project, GHGT-13 Proceedings, Energy Procedia, this volume.